TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

# JANI URAMA
# IMPROVING PERFORMANCE IN MULTI-RADIO HETEROGENEOUS NETWORKS

Master of Science thesis

Examiners: Prof. Yevgeni Koucheryavy and Dr. Sergey Andreev
Examiners and topic approved by the Vice Dean for Education of the Faculty of Computing and Electrical Engineering on March 1st, 2017

# ABSTRACT

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Internet access has become commonplace in the modern world. As the number of users and amount of traffic in the Internet keep rising exponentially, and the requirements of novel applications are becoming more stringent, there is a clear need for new networking solutions. One of the key concepts in solving the challenges of the upcoming 5G era of communications will be heterogeneous networks, where the users can gain benefits by either being connected to multiple different radio technologies simultaneously or smoothly changing from one network to another based on their needs. The main question this work targets to answer is: how can we utilize the concept of heterogeneous networks and the simultaneous connections to multiple radio technologies to improve throughput, latency, and, reliability, in addition to making the overall user experience better? In order to offer concrete answers to this question, a multi-purpose automated vehicular platform prototype equipped with multiple radio access technologies was constructed to show the potential performance gains provided by the use of multi-radio heterogeneous networks in terms of throughput, latency and reliability. Potential drawbacks of using multiple radio interfaces at the same time were also considered. The vehicular platform prototype was discovered to be a flexible research framework for technologies concerning heterogeneous networks and helpful for envisioning future use cases for heterogeneous networks.

# TIIVISTELMÄ

**JANI URAMA**: Suorituskyvyn parantaminen heterogeenisissa moniradioverkoissa
Tampereen teknillinen yliopisto
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Aina saatavilla oleva Internet-yhteys on osa arkipäiväämme. Internetin käyttäjien lukumäärän ja liikenteen määrän kasvaessa yhä edelleen sekä uusien sovellusten vaatimusten käydessä yhä vaativammiksi on selvää, että ennen pitkää tarvitsemme uusia verkkoteknisiä ratkaisuja. Yksi tulevan 5G-aikakauden haasteiden ratkaisuista on kehittää heterogeenisia verkkoja, joissa käyttäjät voivat hyödyntää yhteyksiä moneen eri verkkotekniikalla toteutettuun verkkoon joko samanaikaisesti tai sulavasti liikkuen verkosta toiseen. Kysymys, johon tämä työ pyrkii vastaamaan, kuuluu seuraavasti: kuinka voimme hyödyntää heterogeenisten verkkojen konseptia eli samanaikaisia yhteyksiä moneen verkkoon parantaaksemme yhteyksien nopeuksia, vasteaikaa sekä luotettavuutta, sen lisäksi että teemme käyttökokemuksesta miellyttävämpää? Vastausten etsimistä varten rakennettiin monikäyttöisen automatisoidun ajoneuvon prototyyppi, joka varustettiin usealla langattomalla verkkotekniikalla. Prototyyppiä käytettiin osoittamaan millaisia hyötyjä heterogeenisista verkoista on saavutettavissa nopeuden, vasteajan ja luotettavuuden suhteen. Myös heterogeenisten verkkojen haasteita ja haittapuolia pohdittiin. Prototyyppi todettiin joustavaksi alustaksi heterogeenisiin verkkoihin liittyviin tutkimuksiin ja tulevaisuuden käyttökohteiden visiointiin.

# PREFACE

This work concludes the long journey that started about three years ago when I was invited to work with a certain research group that, despite its name, turned out to be a rather warm and cozy place to practice the traditional Finnish quietude.

Dear members of the W.I.N.T.E.R. group, you might have noticed that I am not a man of many words – except in writing, sometimes – so I'll try to keep this short for once.

First of all, my gratitude goes to Roman Florea and Aleksandr Ometov for showing me the ropes at the beginning, and Sergey Andreev for his valuable support and guidance over the years. I would also like to acknowledge Yevgeni Koucheryavy for the work he does for our research group. Kiitokset Mikhail Gerasimenkolle yhteistyöstä projektien kanssa ja tsemppiä suomen opiskeluun. I would like to express my sincerest thanks to the rest of the research group members, the teaching assistant team and all the other people I have worked with during the past three years.

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Tampere, 21.11.2017

Jani Urama

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# LIST OF ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| 3GPP | 3rd Generation Partnership Project |
| 4G | Fourth Generation (mobile radio network) |
| 5G | Fifth Generation (mobile radio network) |
| AP | Access Point |
| API | Application Programming Interface |
| AR | Augmented Reality |
| BS | Base Station |
| CPU | Central Processing Unit |
| EPC | Evolved Packet Core |
| GPIO | General Purpose I/O |
| GPS | Global Positioning System |
| HDMI | High Definition Multimedia Interface |
| IEEE | Institute of Electrical and Electronics Engineers |
| IETF | Internet Engineering Task Force |
| IoT | Internet of Things |
| ISM | Industrial, Scientific, and Medical |
| ITU | International Telecommunication Union |
| LAN | Local Area Network |
| LTE | Long Term Evolution |
| MAC | Medium Access Control |
| MPTCP | Multipath Transmission Control Protocol |
| NAT | Network Address Translation |
| RAT | Radio Access Technology |
| RAM | Random Access Memory |
| RFC | Request For Comments |
| RJ45 | Registered Jack 45 |
| RSSI | Received Signal Strength Indicator |
| SDN | Software Defined Networking |
| SCTP | Stream Control Transmission Protocol |
| SNR | Signal-to-Noise Ratio |
| TCP | Transmission Control Protocol |
| TR | Technical Report |
| TS | Technical Specification |
| TUT | Tampere University of Technology |
| UDP | User Datagram Protocol |
| USB | Universal Serial Bus |

| | |
|---|---|
| UE | User Equipment |
| VPN | Virtual Private Network |
| VR | Virtual Reality |
| WLAN | Wireless Local Area Network |
| WPAN | Wireless Personal Area Network |
| mMTC | Massive Machine Type Communications |
| mmWave | Millimeter Wave |
| uMTC | Ultra-reliable Machine Type Communications |

# 1. INTRODUCTION

## 1.1 Motivation

Internet access has become commonplace in the modern world. In the developed countries, the Internet can be accessed virtually from anywhere at any time. Thanks to that, the amount of users and traffic on the Internet has been rising exponentially in the past years. According to the Cisco Visual Networking Index white paper from June 2017, [1] the annual global IP traffic exceeded 1.2 Zettabytes[1] in 2016, and there does not seem to be an end to this trend as the global IP traffic is predicted to grow almost threefold by 2021. Traffic from wireless and mobile devices is expected to grow faster than traffic from wired devices in the coming years. Wireless and mobile traffic are predicted to account for almost two-thirds of all traffic in five years' time, in contrast to the current almost equal ratio. [1]

What is remarkable is that the vast majority of all IP traffic is video data, accounting for 73 % of all IP traffic in 2016 [1]. While advances in video encoding techniques, such as H.265/HEVC (High Efficiency Video Encoding) [2] and beyond, can be used to slow down the ever-growing throughput demands of high resolution and high frame rate videos, efficient video compression alone is not enough to handle the capacity problem, nor can it do much about the latency or reliability side of the problem as there are other kinds of traffic than video data in the Internet as well.

Video data can be divided roughly into two categories based on whether it is time sensitive or not. Examples of time-sensitive video traffic include live streams and video calls, while examples of time insensitive video traffic include downloaded videos and video on demand (VoD) services such as Youtube and Netflix. The Cisco white paper shows that in 2016, 13 % of Internet video traffic was live video and that by 2021 the live video traffic is expected to grow 15-fold, while all Internet video is expected to grow fourfold, which would result in a nearly equal ratio of live video and VoD by 2021. The sheer amount of time-sensitive video data will pose serious challenges to the future networks due to them requiring both high capacity and low latency.

[1]Zettabyte equals to $10^{21}$ bytes.

One of the largest emerging paradigms is the Internet of Things (IoT), where not only people but also machines and services can connect to each other and share information. The effect of IoT on the future networks is expected to be mainly due to the number of connections exponentially growing. While the raw traffic amounts generated by IoT devices are not as substantial when compared to video traffic [3], the astounding numbers of devices, and therefore connections as well, might overwhelm the network when all the devices are competing over the same medium and limited resources.

The new applications of the upcoming era of communications, which could be associated with names such as Internet of Things, Internet of Everything, Industry 4.0, or Web 3.0, call for more and more stringent requirements in the form of high throughput, ultra-low latency, and extremely high reliability [4, 5]. It is apparent that current network infrastructure and networking technologies eventually cannot handle the growing data amounts, nor can they currently provide the low levels of latency desired by the emerging applications. Thus, there is a clear need for new networking solutions. One of the key concepts in solving the challenges of the upcoming era will be *heterogeneous networks*, where the benefits of multiple networking technologies can be flexibly leveraged to accommodate the constantly changing requirements of each and every user and application [4, 6–8].

## 1.2 Objectives

The objective of this work is to research and present ways in which heterogeneous multi-radio networks can improve performance as compared to traditional wireless networks. While heterogeneous networks do not have to be wireless in nature, this work is primarily concerned with wireless multi-radio heterogeneous networks.

The main performance aspects that will be analyzed in this work are *reliability*, *latency*, and *throughput*. The improved performance is required in order to satisfy the growing demands of future communication networks and to enable the emerging IoT applications and services along with other novel use cases expected to arrive with the fifth generation (5G) of mobile networks.

In order to accomplish the objectives of this work, a multi-purpose automated vehicular platform prototype equipped with multiple radio access technologies was built to acquire concrete results that show the potential performance gains of multi-radio heterogeneous networks, provide a flexible research platform for technologies concerning heterogeneous networks, and demonstrate use cases for heterogeneous networks.

## 1.3 Scope and structure of this work

The scope of this work is limited to addressing the current state of heterogeneous networks and the technologies closely related to them, exploring performance related aspects of wireless multi-radio heterogeneous networks and how to improve them further, and envisioning future use cases for heterogeneous networks where the improved performance is of utmost importance.

Figure 1.1 visualizes the components of this work in smaller detail. This work deals with mainly a subset of technologies related to wireless networks (detailed in the small boxes around the larger box in the middle of the figure) and how those technologies can be utilized together to form heterogeneous networks. Other important concepts related to this work detailed in the figure are multipath protocols and IoT. The primary result presented in this work – the improvement of network performance by utilizing multi-radio heterogeneous networks – is pictured in the box in the top-right corner of the figure. The details of each chapter in this thesis are as follows:

- In Chapter 1, the topic is introduced by detailing the motivation behind this thesis, plus the objective, scope, and structure of this thesis.
- In Chapter 2, the primary performance metrics discussed in this work are defined. The other sections of this chapter describe the necessary background knowledge required to understand the importance and purpose of wireless multi-radio heterogeneous networks, starting from wireless networks in general, gradually going deeper into the details, leading up to the 5G mobile networks

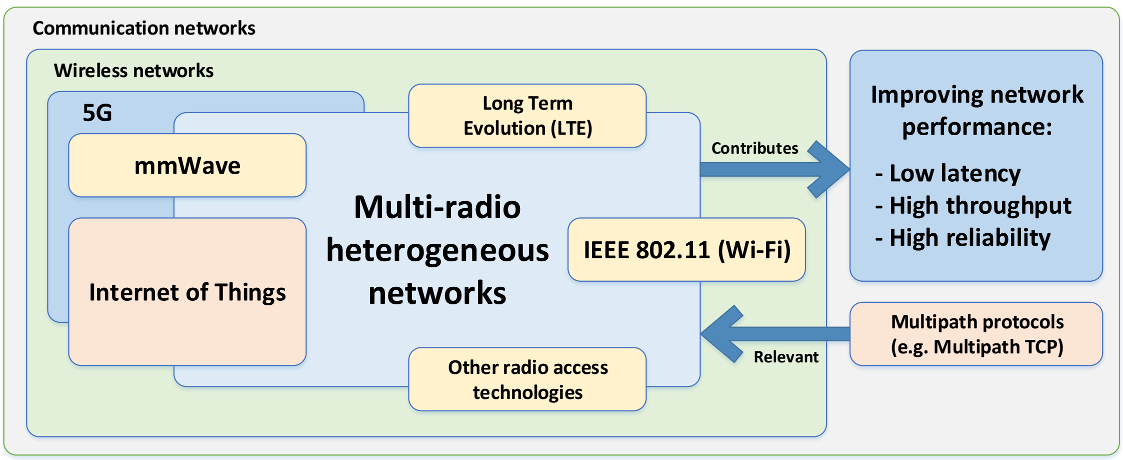



*Figure 1.1 Scope of this work visualized.*

while observing how heterogeneous networks and IoT are related to the broader picture.

- In Chapter 3, the current state of heterogeneous networks and technologies relevant to multi-radio heterogeneous networks is discussed. The concept of multi-connectivity is clarified and an overview of radio access technologies related to heterogeneous networks in the context of this work is given. Protocols from recent years which could be used to enable mobility between networks or multi-connectivity are shortly introduced – with a focus on multipath TCP (MPTCP).

- In Chapter 4, the multi-purpose automated vehicular platform built for the purpose of exploring the possibilities of wireless multi-radio heterogeneous networks in 5G mobile radio networks is presented. The reasoning behind the platform choice is detailed. The design, architecture, and implementation of the platform are disclosed in detail. Additionally, the challenges and limitations that were met with during the implementation process are discussed.

- In Chapter 5, the evolution of the heterogeneous test network located at Tampere University of Technology and the testing scenarios used to evaluate the performance of wireless multi-radio heterogeneous networks when compared to traditional wireless networks are detailed. Results obtained from the three phases of testing by utilizing the aforementioned vehicular platform and traditional user equipment are presented and discussed.

- Finally, in Chapter 6 the conclusions are presented along with future work related to wireless multi-radio heterogeneous networks and the multi-purpose automated vehicular platform.

# 2. BACKGROUND

This chapter gives an overview of the relevant technical background information in relation to this work. More specifically, Section 2.1 defines the performance metrics used in this work and the following sections give a primer on the relevant networking technologies helpful to understand the importance and purpose of multi-radio heterogeneous networks.

The technology overview starts from Section 2.2 describing wireless networks in general, followed by taking a look at the emerging paradigm known as the IoT in Section 2.3, leading into the 5G mobile networks in Section 2.4 while observing how heterogeneous networks relate to IoT and 5G.

## 2.1 Performance metrics

### 2.1.1 Latency, throughput, and reliability

The main performance metrics considered in this work are *latency*, *throughput* and *reliability*. While the meaning of the former two is clear and well-defined in the context of computer science and telecommunications, the definition of reliability might be hazy. For reference, the Oxford Dictionary of Computer Science [9] gives the following definitions for the aforementioned terms:

- *latency* – A measure of how long it takes for a given job or piece of work to be completed, or for a message to make its way from source to destination.
- *throughput* – A figure-of-merit for a computer system in which some description of operating rate such as instructions per minute, jobs per day, etc., is used. It is a measure of how much work gets done in a given time interval.
- *reliability* – The ability of a computer system to perform its required functions for a given period of time. It is often quoted in terms of percentage of uptime, but may be more usefully expressed as mean time between failures.

For the purposes of this work, in the context of multi-radio heterogeneous networks, reliability is clarified to refer to the ability of a device to successfully transmit information utilizing all or any of the radio access technologies available to it. In the case when information is duplicated and transmitted over multiple radio access technologies (RATs) at the same time, the device can be considered to have reliable connectivity as long as information can be successfully exchanged over at least one RAT.

Reliability can be quantified, either on system level or for each radio access technology separately, by a combination of various metrics such as a ratio of successfully sent packets versus all packets sent or connection uptime or availability percentage.

### 2.1.2 Signal-to-noise ratio

The signal-to-noise ratio (SNR) compares the strength of the signal to the level of the background noise. The definition of SNR is shown in Formula 2.1 [10]:

$$SNR = \frac{P_{signal}}{P_{noise}}, \tag{2.1}$$

where $P_{\text{signal}}$ and $P_{\text{noise}}$ are the power levels of the signal and noise, respectively. The signal-to-noise ratio can also be expressed in decibels, as shown in Formula 2.2 [10]:

$$SNR_{dB} = 10\, log_{10} \frac{P_{signal}}{P_{noise}} dB. \tag{2.2}$$

The SNR can also be used in conjunction with the Shannon-Hartley theorem in order to calculate the theoretical maximum throughput in a noisy channel of a certain bandwidth. This theorem and Shannon's work in *A Mathematical Theory of Communication* [11] was groundbreaking in the history of wireless networks, as it made error-free transmission possible when restrictions for the data rate and the SNR are considered [12]. The Shannon-Hartley theorem is shown in Formula 2.3 [10]:

$$C = B\, log_2\,(1 + SNR), \tag{2.3}$$

where C is the channel capacity in bits per second, B is the bandwidth of the channel measured in Hertz and SNR is the signal-to-noise ratio defined in Formula 2.1. The theorem also shows why millimeter wave (mmWave) technology will be important for

5G networks, as mmWave enables communication in the extremely high frequency (EHF) band ranging from 30 to 300 GHz, where there is much more room to utilize channels with wider bandwidth and thus improve throughput.

## 2.2 Wireless networks

Wireless connectivity has become part of our everyday life as indicated by the ever-growing amounts of wireless and mobile traffic [13], the omnipresence of various devices equipped with wireless capabilities such as smartphones, wearables, smart home equipment etc. and the possibility to connect to a WLAN (wireless local area network) in just about any urban area [14]. Thus, it is apparent that wireless networks are of high importance in today's world. In fact, it could be said that successful technologies are invisible – you do not notice that the technology is there, yet it is present in your daily experiences.

One of the main enablers of wireless networks is Wi-Fi[1], which is a brand name for devices with wireless connectivity based on the family of IEEE (Institute of Electrical and Electronics Engineers) 802.11 standards. Wi-Fi is so ubiquitous with its widespread market share that it could be considered to be synonymous with WLANs or wireless connectivity in the eyes of the common user [12]. The same phenomenon can be observed with other products and services, which are arguably better known by their brand names. This usually leads to a situation where the brand name becomes a common word in the colloquial English language. Examples include *post-it notes* for a self-adhesive notepaper and *googling* for performing an Internet search, for example.

It should be pointed out that against common belief, Wi-Fi does not mean *wireless fidelity*. The misunderstanding stems from a slogan the Wi-Fi Alliance was using in the past in order to create an allusion with *high fidelity* (Hi-Fi). However, Wi-Fi is a made up word that allegedly does not mean anything. [15, 16]

Obviously, wireless connectivity is not limited to Wi-Fi or WLANs as there exists a plethora of other wireless technologies and protocols for various purposes and use cases, such as Bluetooth for wireless personal area networks (WPAN) and wearables, LTE (Long Term Evolution) for mobile radio networks and mmWave (millimeter wave) for extremely high frequency, high data rate links.

Wireless networks have to deal with certain challenges due to their inherent nature, such as interference from physical objects or other wireless signals. One of the

[1] https://www.wi-fi.org/

primary challenges of wireless networks is the limited amount of frequency spectrum available for practical use in radio networks due to the laws of physics, which has lead to international agreements regulating the use of the spectrum. [12] The problem of limited spectrum has lead to developing solutions on how to utilize the limited spectrum as efficiently as possible, such as advanced modulation schemes which are able to carry more bits of information per symbol.

Predicting traffic demands in future mobile networks will become more difficult. While the traffic demands can be predicted fairly accurately when they follow the standard patterns, in the future due to new use cases there will likely be cases of sporadic and spontaneous traffic spikes due to, for example, events and novel use cases by third parties.

One of the first examples of these spontaneous traffic spikes has already been seen recently in July 2017. During an event related to the location-based augmented reality (AR) game *Pokémon GO*[2] developed by Niantic, around 20 000 people gathered into Grant Park in Chicago in hopes of attaining rare prizes related to the game. As a result, the mobile networks could not handle the load and the event resulted in a failure as people were unable to connect to the game, leading the organizer having to issue refunds to the attendees and taking a blow to their reputation. [17, 18]

Would it have been possible to avert the failure? Allegedly, not all mobile operators were properly prepared for the event, or they might have had decided against bringing additional infrastructure to the site due to it being costly and not worth it to the operators [17, 19]. Either way, this case presents a new kind of problem, where people can gather somewhat spontaneously in a place where there is not enough network infrastructure in place to handle the sudden explosive increase in traffic demand and the number of connections. The solutions are an open research question with some of them being envisioned in the form of truly mobile networks, where the access points can flexibly move to where there is demand for them, possibly carried by drones, or even balloons high in the atmosphere [20].

Be it as it may, the fact is that traffic amounts are growing and an ever-growing portion of the traffic is from wireless and mobile networks [13]. Latency and reliability demands are also becoming more difficult to meet as applications with more and more stringent requirements such as self-driving cars and remote AR or virtual reality (VR) connections emerge. Thus, we need to improve the capabilities of wireless communication networks.

[2]https://www.pokemongo.com

## 2.3 Internet of Things

The Internet where not only people but machines and services as well can connect to each other and share information is named the Internet of Things (IoT). The Oxford Dictionary of Media and Communication [21] defines IoT as follows:

- *Internet of Things* - The embedding of computer hardware and software into everyday objects which can then be organized into a virtual network of "terminals", providing configurable information about their status and location, remotely controlling or being controlled by smartphones and computers. The term was proposed by Kevin Ashton, a British technologist, in 1999. The ubiquity and low cost of microprocessors have led increasingly to their being placed in a range of everyday objects.

IoT is a paradigm that has taken shape over the past tens of years, and yet only recently the advances in technology have made it possible to get close to meeting the requirements of IoT and thus realizing the IoT vision [4], which is commonly phrased as:

> "a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual "Things" have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network" [6, 22].

While it is still not completely clear what IoT will exactly become in the end [23], one point is apparent: IoT will be a very complex network, which utilizes a multitude of different protocols to connect between various types of networks in order to provide ubiquitous connectivity for IoT devices. As such, heterogeneous networks are one of the key enabling technologies and concepts in order to make IoT a reality. [4, 6]

Machine Type Communications (MTC) is expected to be tightly related with 5G and IoT. Machine Type Communications can be roughly divided into two major categories: massive Machine Type Communications (mMTC) and ultra-reliable Machine Type Communications (uMTC), which have distinctly different requirements. The former is about deploying possibly billions of low-cost devices and sensors and providing them with wireless connectivity, while the latter is about providing high availability and reliability along with low latencies. [24] Example use cases for mMTC include smart homes, cities and other environments filled with sensors, and example use cases for uMTC include assisted driving or even self-driving cars, and mission-critical control applications for industry.

Thus, the IoT related applications are expected to have highly varying requirements. The future networks must be able to satisfy all of these requirements either at the same time or they must be able to adapt to the ever-changing requirements. 5G networks, which are detailed in the following section, are expected to help enable these stringent requirements and further aid the realization of IoT [4].

## 2.4 Fifth generation mobile networks (5G)

The upcoming 5G mobile networks aim to address the stringent demands of IoT, MTC and other emerging applications. Research initiatives by academia and industry have identified the following requirements for 5G networks [25–29]:

- Data rates measured in gigabits per second (Gbps)
- Extremely low latency (less than 1 ms round trip time)
- Support enormous numbers of connected devices per cell (tens of thousands)
- Near 100 % availability and coverage
- Better energy efficiency and battery life

There are three dimensions in which the capacity of wireless communication networks can be expanded: spectral efficiency, frequency (bandwidth) and space. The following paragraphs explain in which ways technologies related to each of the dimensions are expected to be advanced in order to enable high data rates for 5G.

As coding schemes are approaching the theoretical limit for channel capacity defined by the *Shannon limit* [30], research for improving spectral efficiency has been focused on advanced multiple-input multiple-output (MIMO) techniques such as Massive MIMO [26]. MIMO techniques are based on utilizing multiple antennas on both the receiving and transmitting ends to transmit and receive multiple signals at the same time, over the same radio channel by utilizing space-time signal processing and exploiting multipath propagation [31]. Details of MIMO operation fall outside the scope of this work.

Millimeter wave (mmWave) is a term for wireless technologies operating in the upper end of super high frequency (SHF) and extremely high frequency (EHF) ranges, which correspond to 3-30 GHz and 30-300 GHz ranges, respectively [32]. The name mmWave originates from the fact that in the EHF range the wavelength is measured in millimeters. Technology for mmWave communication will be important for 5G networks because it enables utilization of the EHF band, where there is much more room to utilize channels with wider bandwidth and thus improve throughput.

Expanding capacity in the frequency dimension is limited by international regulations and the high cost of mmWave electronics [26]. Furthermore, the higher the frequency, the higher is the free-space path loss in relation to the distance according to the *Friis formula* [32, 33]. In addition to that, in certain EHF ranges – most notably in the unlicensed band around 60 GHz – there is additional atmospheric and rain attenuation due to absorption from oxygen and water molecules [25, 32], which makes these frequencies unsuitable for long-range transmissions. However, in ultra-dense deployments of cells, this can be seen as a benefit because it makes more frequent reuse of frequencies feasible due to reduced interference from nearby cells using the same frequencies.

Ultra-densification, which means utilizing many small cells with lower transmit powers, is viewed to be an important aspect of 5G in order to provide improved capacity at low costs [26, 29, 34]. The idea is simply to increase the total number of cells by a large factor and thus reduce the distance between cells, which makes it possible to serve a larger amount of users in a unit of area.

Multi-radio heterogeneous networks – as a combination of all the networks using different radio access technologies – belong to the spatial dimension of 5G. In short, by connecting simultaneously to multiple networks, the combined capacity of all the networks can be leveraged at the same time, in addition to reaping the benefits related to latency and reliability. Chapter 3 will explain multi-radio heterogeneous networks in more detail.

The unit of spectral efficiency is bits per second per Hertz (bits/s/Hz), which means that improvements in spectral efficiency allow us to get more mileage out of the limited amount of radio spectrum available. The unit of bandwidth is Hertz (Hz), which means wider bandwidth allows us to transmit more data on a channel at a time. Now, taking a closer look at the units defined above, we can notice that improvements in spectral efficiency and bandwidth width are multiplicative. For example, if spectral efficiency is improved tenfold and the available bandwidth is made ten times as large, the resulting improvement in data rates is 100-fold for a cell. Finally, if we increase the total number of cells by a factor of 10, the total capacity of the system is now 1000 times as large as it was before.

Even though the round trip time (RTT) of less than 1 ms has been identified as a target for 5G, there is very little work explaining how this requirement could be achieved and thus it is still considered to be an open question [25, 26]. As radio waves cannot travel faster than the speed of light ($3.0 \cdot 10^8\, m/s$) and propagation speeds in copper wires and fiber optics are roughly 30 % slower [10], it means that the content accessed cannot be physically located further than 100-150 km away – without taking any processing delays into account. Therefore, in practice the content has to be located much closer to the user, likely at the very edges of the network in order to compensate for the processing delays.

# 3. MULTI-RADIO HETEROGENEOUS NETWORKS

In this chapter, the basics of multi-radio heterogeneous networks and technologies closely related to them will be explained. In the context of communication networks, a heterogeneous network means a network which is a combination of other networks using different access technologies. In this work, the focus is on multi-radio heterogeneous networks, in which multiple radio access technologies are used, possibly even at the same time, forming a multi-connected multi-radio heterogeneous wireless network. Devices in such networks are equipped with multiple radio access interfaces in order to gain benefits related to throughput, latency, and reliability. Disadvantages include increased power consumption and complexity.

This chapter begins with an introduction to heterogeneous networks in Section 3.1 describing heterogeneous networks and their challenges in general. In Section 3.2, the concept of multi-connectivity is explained, followed by taking a look at protocols related to heterogeneous networks in Section 3.3. Finally, an overview of important radio access technologies related to heterogeneous networks in the context of this work is given in Section 3.4.

## 3.1 Introduction to heterogeneous networks

One of the key concepts in solving the challenges of the upcoming era of communications will be heterogeneous networks, where the users can reap the benefits by either being connected to multiple different networks simultaneously or smoothly changing from one network to another based on their needs [4]. Figure 3.1 describes a generic topology of a multi-radio heterogeneous network.

At the center of the figure, there is an LTE cell tower that is providing cellular connectivity over an area depicted by the largest ellipse. Further, there are other access points providing additional coverage with various radio access technologies such as the Wi-Fi access points and a high-speed mmWave 5G access point.

Other devices in the figure include smart sensors, which have connectivity to the

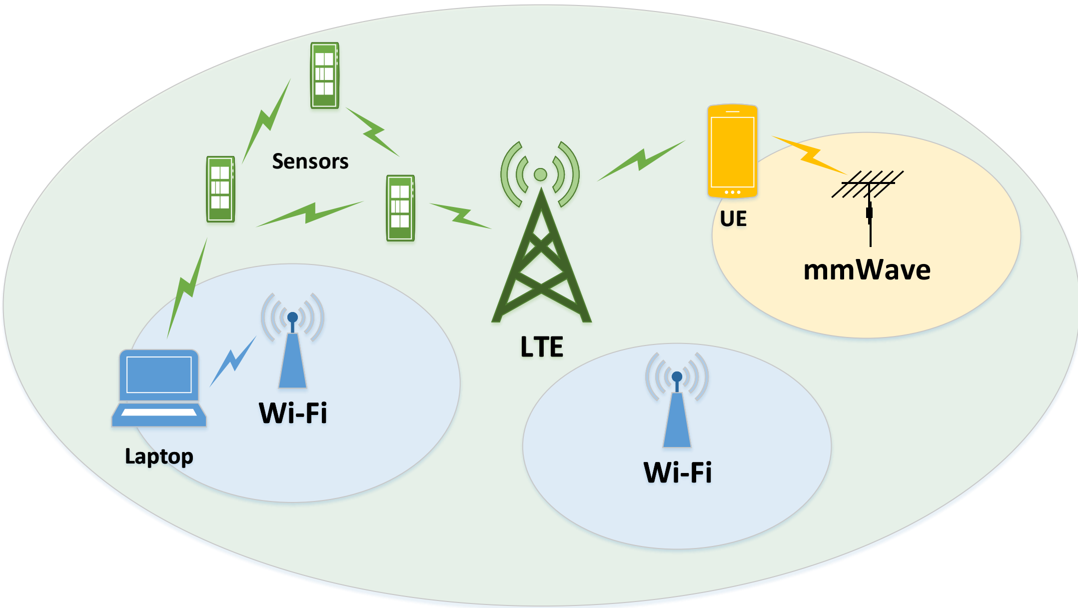



***Figure 3.1*** *A generic heterogeneous network topology depicting devices connected to multiple radio access technologies at the same time.*

cellular network and they have formed their own IoT sensor network between themselves. The mobile devices shown include the UE (user equipment) that is connected to both LTE and 5G cellular networks and the laptop that has connected to the Internet via a Wi-Fi access point and via the IoT sensor network. Additionally, the laptop user can utilize the data and services provided by the sensor network at extremely low latencies.

However, there is a problem that has to be solved before the potential of heterogeneous networks can be fully realized: the specifications for the underlying technologies and protocols of the Internet were drafted over 40 years ago to accommodate the needs of that time period. Basically, it was not taken into account that the Internet could someday be trivially accessed on the go from mobile devices, or that the devices could be constantly switching from a wireless network to another as the user carrying the mobile device moves.

While those protocols certainly have been evolving over the course of time, one crucial problem with them still remains: when a mobile device changes from a wireless network to a wireless network of a different type, e.g. from Wi-Fi to LTE, all of the existing connections have to be re-established because they are bound to the address of the Wi-Fi interface, and the data cannot automatically find its way to the LTE interface, which has a completely different address. In other words, the current protocols cannot be aware of more than a single address at a time.

The solution to this problem is easy on paper: develop new protocols which are aware of multiple addresses at a time. However, the Internet has grown way bigger than anyone imagined and introducing new protocols to the entirety of Internet in a way that would work harmoniously with all the existing parts is challenging, to say the least [35]. The process could be compared to trying to change the fundamental ways of how a massive multi-national megacorporation works – a process that would be slow and painstaking.

Let us imagine that we have protocols at our disposal, which are capable of utilizing multiple different networks simultaneously. Now, the question is: how can we utilize the concept of heterogeneous networks and the simultaneous connections to multiple networks to improve throughput, latency, and reliability, plus to make the overall user experience better?

Improving throughput is trivial, at least in theory, since if we have a certain amount of capacity available on one network and some more on another network, being connected to both of them should let us use the total amount of capacity. In practice it is going to be a bit more difficult, as if we split the data and send parts of it over one network and the rest over another, the data might find its way through one network faster than via another, and thus the data might arrive in an incorrect order to the receiving end. It would not be a good user experience to read a book which has the pages in a wrong order.

A concept for improving latency involves sending copies of same data over all available networks, putting the one that arrives the fastest to the destination into use and discarding the rest. In the same vein, sending multiple copies of the same data creates redundancy, which in turn improves reliability, as it is much less likely for all copies of the same data become lost than for one copy. However, sending redundant copies of large amounts of data to the Internet is undesired from the network's point of view as it causes congestion. Additionally, having multiple network interfaces active at the same time increases energy consumption. Therefore, a balance should be found between improving performance, energy efficiency and overloading the networks.

The following is a concrete example of how heterogeneous networks and protocols that are aware of multiple networks can improve the user experience: let us imagine you are at home connected to your local Wi-Fi network and you have a large file download active on your smartphone. Suddenly, your friend makes a video call to your smartphone. However, your Wi-Fi connection does not have enough capacity to handle both the download and the video call smoothly at the same time, so the smartphone decides to connect the video call over the previously inactive cellular data connection instead of the active Wi-Fi connection. Moreover, you decide to leave the house and you take your smartphone with you. However, you have now moved outside the range of your house's Wi-Fi connection while the file download was still running. Luckily, your smartphone had established the connection using a protocol that is aware of other networks and thus was able to continue the download through the cellular connection on the go. Otherwise, the download would have had stopped and you would have possibly had to start it all over again.

## 3.2 Multi-connectivity

In the context of this work, multi-connectivity means that a device has the possibility to be simultaneously connected over two or more different radio access technologies. In other contexts, multi-connectivity may also mean simultaneous connectivity to two or more cells using one radio access technology [36], but these situations fall outside the scope of this thesis. It should also be mentioned that multi-connectivity is not limited to wireless radio access technologies as wired Ethernet can also be used as one of the connections. However, this work considers primarily wireless networks.

For the purposes of this work, multi-connectivity is categorized into the following four main classes based on how the UE or the network can leverage multi-connectivity:

- Offloading or load-balancing only – The UE only ever uses a single RAT for an application at a given time. The UE may have separate applications connected over different RATs. In case connectivity on one of the RATs goes down, the UE can tear down the existing connections on that RAT and re-establish the connections on another RAT. A typical use case on a smartphone would be to offload some connections from the primary cellular link to the secondary Wi-Fi connection in order to alleviate congestion on the cellular link [37]. Offloading is not studied in this work in further detail.

- Application layer multi-connectivity – The UE runs applications which have been specifically configured to utilize multiple RATs simultaneously by establishing a separate connection for each RAT. The application servers are likewise configured to handle connections from multi-connected UEs. One use case is to duplicate mission-critical data and send it over all available RATs in order to improve reliability. This approach is used by the control connection between the vehicular platform detailed in Chapter 4 and its remote client application.

- Proxied multi-connectivity – The UE and its applications can use all of the RATs available at the same time with implementation specific limitations due to the use of a proxy and network address translation. In this type of multi-connectivity, there is a proxy located in the operator's or ISP's (Internet service provider) network which serves as a gateway for all connections originating from the UE's different RATs. A project the author was part of [38] used an approach where the connections originating from a virtual interface of the UE are tunneled through a VPN (virtual private network) to the proxy, which performs NAT (Network Address Translation) in order to act as the public IP interface of the UE. Software defined networking (SDN) is used to dynamically route and load-balance the data flows through the tunnels established on the available RATs. A similar proxied approach where the tunnels and SDN are replaced with MPTCP [39] has been shown by Coninck et al. [40] and by KT (former Korean Telecom) in their commercial deployment of GiGA LTE [41].
- True multi-connectivity – The UE and its applications can use all of the RATs available in a way that is transparent to the applications. This is the most desirable category of multi-connectivity, but the Internet and TCP were not designed with today's mobile multi-connected devices in mind [42]. Thus, there is a need for new multipath capable protocols, such as MPTCP or Stream Control Transmission Protocol (SCTP) [43], which can enable true multi-connectivity. However, the structure of the current Internet makes it challenging to design multipath protocols due to the presence of so called middleboxes (firewalls, NATs, etc.), which might tamper with the contents of the packets, which in turn makes it difficult to identify which multipathed sub-connection the packet belongs to [42, 44] Additionally, both ends of the connection must support the multipath protocol. This work focuses on MPTCP as the multipath protocol of choice. Operation of MPTCP is explained in more detail in Section 3.3 and the results of a MPTCP performance test in a heterogeneous network are discussed in Section 5.4.

The aforementioned categories of multi-connectivity are visualized in Figure 3.2. Leftmost network illustrates the offloading and load-balancing case, where two separate applications (shown as solid and dashed lines) have established connections over different RATs. Each application here utilizes only one RAT at a time. Next, the second network from the left UE demonstrates the application layer multi-connectivity case, where one application has established one connection over each RAT and sends the same data on both connections to attain better reliability. The following network pictures the proxied multi-connectivity case, where the UE has established tunnels to the proxy and SDN is used to dynamically control which

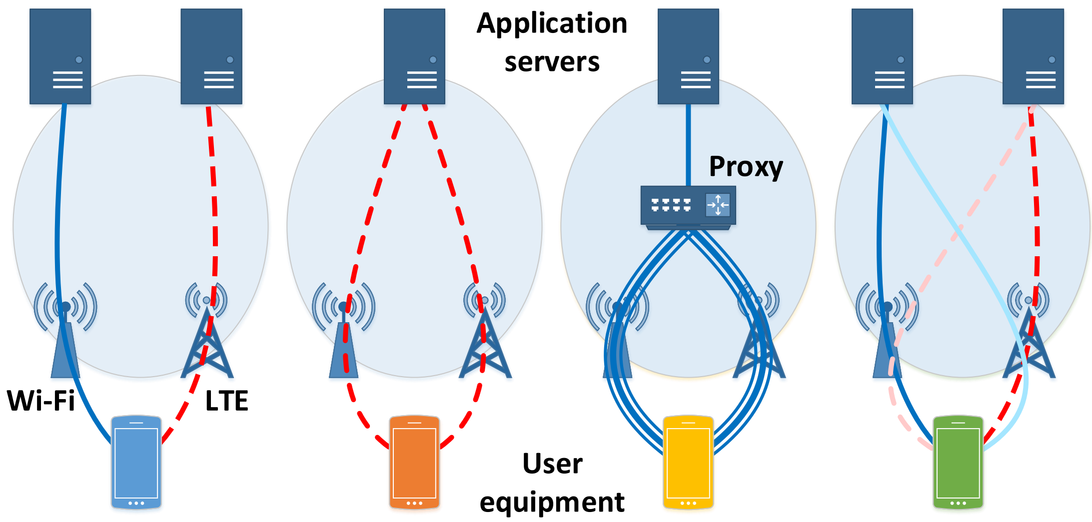



***Figure 3.2*** *Types of multi-connectivity illustrated. From left to right: offloading, application layer multi-connectivity (duplicating), proxied multi-connectivity and true multi-connectivity. The solid and dashed lines depict different applications.*

tunnel the data flows are going through. Finally, the rightmost network shows the true multi-connectivity case, where two applications have established multipath subconnections (pictured in darker and lighter color) for each RAT available with the help of a multipath protocol.

## 3.3 Protocols related to heterogeneous networks

Protocols that have been attempting to enable mobility, multi-connectivity or both in the past years include Mobile IP [45, 46], Stream Control Transmission Protocol (SCTP) [43] and Multipath Transport Control Protocol (MPTCP) [39]. The following paragraphs give a short overview of each protocol.

Mobile IP enables nodes to move from one IP subnet to another while preserving connectivity as all traffic is routed via proxies when the node is not connected to its permanent home address [45]. However, Mobile IP hides the address and path changes from the transport layer and therefore causes efficiency problems with TCP's congestion control scheme [44].

Stream Control Transmission Protocol is a transport layer protocol which is aware of multiple IPs per connection similar to MPTCP. However, SCTP is not compatible with the standard network socket API (Application Programming Interface) implemented in modern operating systems [44], and firewalls, NATs (Network Address Translators) and other middleboxes found in today's Internet are unable to process

SCTP packets [47]. MPTCP is designed to take the above-mentioned problems and more into account [39, 44]. The next paragraphs take a closer look at the operation of MPTCP.

MPTCP is a multipath protocol specification published as an experimental standard by the Internet Engineering Task Force (IETF) in 2013 [39]. MPTCP is an extension to the widely used Transport Control Protocol (TCP) [48]. Use of MPTCP is negotiated during the TCP three-way handshake via new TCP options. If it is found that both endpoints of the connection support MPTCP and that there are no interfering middleboxes (e.g., firewalls or NATs, which remove TCP options or otherwise modify packets) to be found in between, the endpoints can negotiate new MPTCP subflows to be added to the existing connection. The subflows work similar to TCP and can be established between any interfaces available to the endpoints.

Discussing the problems encountered during the design of MPTCP [49] and the details of the protocol [39, 44] fall outside the scope of the thesis, so this section will focus on the practical side of matters. As MPTCP operates on the transport layer of the network stack, its operation is transparent to the user. Depending on the implementation of the network stack in the operating system, the operation of MPTCP might be transparent to the applications as well. In order for MPTCP to work, both endpoints of the connection must support it (unless a proxy is used as described in Section 3.2), which limits the practical usability in today's Internet as MPTCP has not been widely deployed at the time of writing.

Notable commercial deployments of MPTCP include an implementation by Apple, who first introduced the protocol in September 2013 in iOS 7, but initially only limited for use in backup connections with the Siri application (virtual assistant that uses artificial intelligence) [50, 51]. With the release of iOS 11 in September 2017, the API (Application Programming Interface) for MPTCP was opened for application developers so that they can make use of MPTCP connections in iOS applications [52]. Additionally, the South Korean operator KT (former Korean Telecom) has ported MPTCP support for Android phones and deployed an MPTCP proxy service in June 2015 [41]. MPTCP is not yet a part of the official Linux kernel, although a reference implementation of MPTCP in the Linux kernel exists and efforts to make MPTCP part of the official Linux kernel are underway [53]. MPTCP support in the official Linux kernel would accelerate multipath protocol adoption significantly [54], as up to two-thirds of web servers are estimated to use Linux [55] and nearly three-quarters of mobile devices are estimated to use Android [56], which is based on the Linux kernel.

In this work, MPTCP is used to demonstrate the possible throughput gains offered by heterogeneous networks – more specifically via the simultaneous use of LTE and Wi-Fi. The vehicular platform detailed in Chapter 4 and the local server were upgraded to support MPTCP during the final phase of the testing process described in Section 5.4.

## 3.4 Overview of related radio access technologies

This section gives a short overview of the radio access technologies important to current and upcoming heterogeneous networks in the context of this work. The radio access technologies introduced are LTE, the IEEE 802.11 family of standards known better collectively under the brand name of *Wi-Fi*, which includes 802.11ad (also marketed as *WiGig* [57]) as an example of a mmWave radio access technology.

LTE is a standard for wireless mobile networks specified by the 3GPP (3rd Generation Partnership Project) Release 8. LTE is commonly referred to as 4G although it does not fully satisfy the requirements of the fourth generation mobile networks specified by the International Telecommunication Union (ITU) [58]. LTE is the first fully packet switched and IP-based cellular architecture. 3GPP TR 25.913 [59] defines peak data rates for LTE as 100 Mbps downlink and 50 Mbps uplink, and the target RTT of less than 10 ms. [60] LTE and other cellular technologies can be thought of as the wireless extension of wired telephone lines.

IEEE 802.11 is a family of standards that specify how to implement the physical and MAC (Medium Access Control) layers in wireless local area networks (WLAN), which are wireless extensions of wired IEEE 802.3 Ethernet connections and local area networks (LAN) [10]. 802.11 standards typically utilize the unlicensed ISM (Industrial, Scientific, and Medical) bands at 2.4 GHz, 5 GHz and 60 GHz frequencies. Each of the amendments to the original 802.11 standard is identified by a letter and the amendments making significant improvements to peak data rates tend to become well-known as vendors use the letters to market their products' capabilities. IEEE 802.11ad is the first amendment that specifies operation at the 60 GHz frequency band [57, 61].

# 4. MULTI-PURPOSE AUTOMATED VEHICULAR PLATFORM

In this chapter, the multi-purpose automated vehicular platform prototype created to evaluate the performance improvements provided by heterogeneous networks is presented. The vehicular platform is equipped with multiple radio access technologies in order to show the potential performance gains of multi-radio heterogeneous networks and demonstrate use cases for heterogeneous networks.

Section 4.1 explains the rationale behind the platform choice. In Section 4.2, the designed operation modes of the vehicular platform are described. The technical details of the vehicular platform and its components are listed in Section 4.3. Finally, Section 4.4 discusses the limitations and challenges that were met with during the implementation process. Solved and to-be-solved challenges alike are reviewed.

## 4.1 Platform choice

Various form factors such as drones and ready-made robot chassis were considered as the framework for the platform. Aquatic and amphibious unmanned vehicles were not considered due to the lack of a suitable testing location, need for additional precautions that should be taken to prevent water damage and increased complexity without apparent benefits. Drones were thought to be an interesting option for the platform due to the ability to operate them in the vast outdoors while utilizing readily available positioning solutions such as GPS (Global Positioning System), and the upcoming European global satellite-based navigation system *Galileo*[1]. However, concerns about the maturity of the technology, regulations concerning unmanned aerial vehicles, weight carrying limits, the risk of crashing, higher cost and higher complexity outweighed the pros of using a drone as the platform of choice.

Therefore, by a process of elimination, it was decided that the first prototype should be a simple terrestrial unmanned vehicle. The last debate was between outdoor and

[1]https://www.gsa.europa.eu/european-gnss/galileo/galileo-european-global-satellite-based-navigation-system

indoor platforms. The platform could have utilized positioning solutions such as GPS in the outdoors. However, ready-made industrial-grade robot chassis suitable for outdoors were deemed to be outside the budget of this project. In addition, outdoor conditions such as dust, rain, and snow, would have imposed additional restrictions and limitations to the design and use of the platform. Thus, the final decision was made to create a vehicular platform for indoor use. Due to the low cost and high availability, a radio-controlled car was disassembled and was chosen to serve as the base framework for the indoor multi-purpose automated vehicular platform prototype.

## 4.2 Design of the vehicular platform

The design of multi-purpose automated vehicular platform embodies the key concepts of the IoT and 5G mobile networks. The envisioned key concepts are heterogeneous networks, mobility, autonomous operation and sensors, which are described in Table 4.1.

***Table 4.1*** *Envisioned key concepts for the multi-purpose automated vehicular platform*

| **Heterogeneous networks** | **Mobility** |
|---|---|
| Multiple radio access technologies<br>Multi-connectivity<br>Improved performance | Moves on wheels, physically<br>Roaming between networks<br>Ubiquitous connectivity |
| **Autonomous operation** | **Sensors** |
| Various modes of autonomous operation<br>Initially: pre-programmed instructions<br>Ideally without human intervention | Proximity sensors<br>Positioning data<br>Signal coverage mapping |

Heterogeneous networks encompass access to multiple radio access technologies, which provide multi-connectivity for the platform and thus improved performance. Mobility in this context means both moving physically from place to place and logically between networks and access technologies – while staying constantly connected with the assistance of multipath protocols. At the initial stages, autonomous operation consists of acting based on pre-programmed instructions and possibly reacting to unexpected circumstances, e.g. obstacles on the way, ideally without human intervention. With sensors and other peripherals mounted on the platform, it can collect and utilize massive amounts of data, such as positioning and signal coverage.

One of the envisioned use cases that ties all of this together is autonomous navigation inside a building with the help of proximity sensors and indoor positioning data while being connected to a multitude of radio access technologies and drawing a signal strength coverage map.

In this thesis, the focus is on the heterogeneous network aspect of the platform. For this purpose, the vehicular platform was designed to function in three different modes, which have distinct latency and throughput requirements:

- *Automated mode*, where the vehicle follows a pre-defined route or pre-scripted commands and sends keep-alive messages periodically. In case the vehicle detects a problem or an obstacle, it may try to navigate around it, or it can notify the operator supervising the platform's operation and change the operating mode into either semi-automated or manual mode. This operating mode is not delay sensitive and the throughput requirements are low assuming no large amounts real-time data is transmitted during the operation.
- *Semi-automated mode*, where the vehicle follows a pre-defined route or prescripted commands and streams video to the remote operator instead of keep-alive messages. The operator can follow the operation of the vehicle and intervene if deemed necessary. The operator can either alter the route or switch the operation into manual mode at any point. This operating mode is not very delay sensitive as the video does not have to be streamed perfectly in real-time. Throughput requirements are higher, but adaptive, as the throughput requirements can be controlled by adjusting the quality of the video stream.
- *Manual mode*, where the vehicle is controlled by the operator remotely. The operator is constantly aware of where the vehicle is owing to the video stream and positioning data. This operating mode is highly delay sensitive due to the real-time controls and real-time video feedback. Throughput requirements in this mode are on the same level as the semi-automated mode, but still adaptive, as the throughput requirements can be controlled by adjusting the quality of the video stream.

Varied delay sensitivity and unbalanced upload/download throughput requirements make the platform to be an excellent basis for testing radio access technology switching and splitting techniques in heterogeneous networks. In each mode, the platform can utilize all radio access technologies simultaneously to maximize performance and satisfy requirements of the applications being tested.

## 4.3 Prototype implementation

This section details the technical features of the vehicular platform. At the core of the platform is a Raspberry Pi 3 model B single-board computer[2]. Full technical specifications of the Raspberry Pi are collected in Table 4.2.

***Table 4.2*** *Technical specifications of the Raspberry Pi 3 model B single-board computer*

| | |
|---|---|
| **Processor** | Quad Core 1.2GHz Broadcom BCM2837 64-bit ARMv8 CPU |
| **Memory** | 1GB RAM<br>Micro SD port |
| **Network** | Built-in BCM43438 Wi-Fi IEEE 802.11 b/g/n<br>Bluetooth Low Energy (BLE) on-board<br>Ethernet port (RJ45) |
| **GPIO** | 40 pins |
| **USB** | Four USB 2.0 ports |
| **Video output** | Full size HDMI port |
| **Audio output** | 3.5mm stereo jack |
| **Power** | 5V micro-USB |

The two motors of the vehicular platform are controlled via the Raspberry Pi's GPIO (General Purpose I/O) pins. The GPIO pins are connected to a custom power feeding circuit built by other members of the research group. This custom-built circuit features a connection to an external 7.2V battery pack, a voltage regulator which converts and stabilizes the battery voltage to the correct 5V voltage for the Raspberry Pi. The battery pack provides power to both the Raspberry Pi and the motors.

The operating system installed on the Raspberry Pi is Raspbian[3] Jessie Lite, which is based on the Debian 8 GNU/Linux distribution[4]. This operating system was chosen as it is the *de facto* operating system for Raspberry Pi computers provided by the manufacturers themselves free of charge. It is simple to operate and community support is readily available.

The platform is equipped with three radio access technologies: Wi-Fi and Bluetooth Low Energy via the built-in chips on the Raspberry Pi, and an external ZTE MF831 USB LTE modem. However, Bluetooth is not used in any of the current testing scenarios.

[2]https://www.raspberrypi.org/products/raspberry-pi-3-model-b/
[3]https://www.raspberrypi.org/downloads/raspbian/
[4]https://www.debian.org/

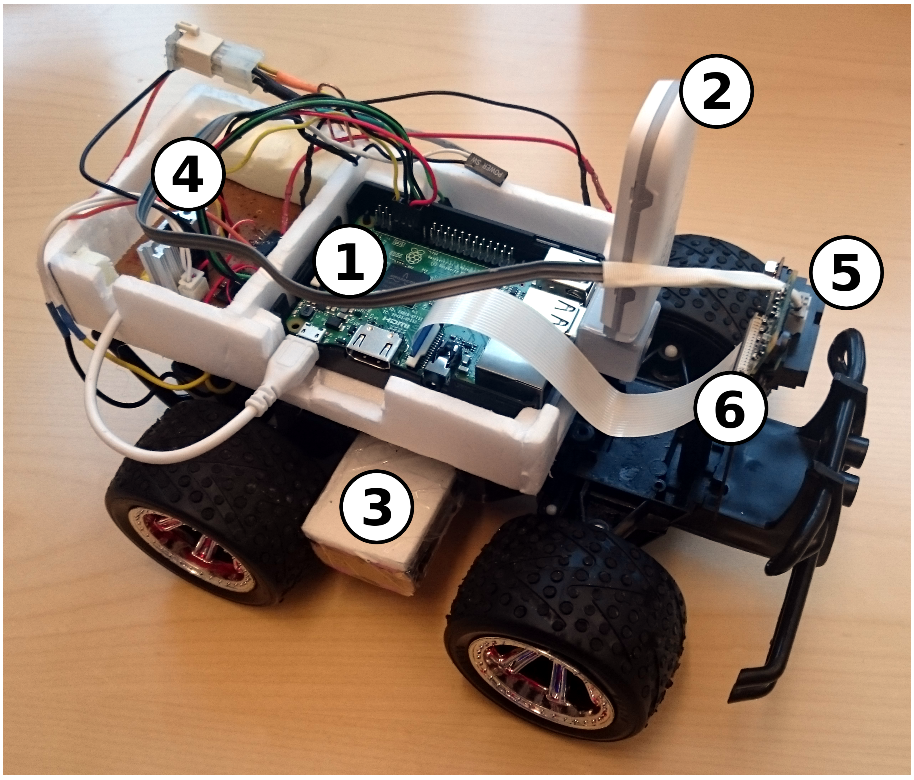



***Figure 4.1*** *A photo of the latest iteration of multi-purpose automated vehicular platform prototype. (1) Raspberry Pi, (2) LTE modem, (3) battery pack, (4) power feeding circuit, (5) proximity sensor and (6) camera are shown mounted on the platform.*

A Raspberry Pi Camera Module v2 is installed to the front of the vehicle. A real-time video stream is suitable for creating a testing environment that is intended for testing applications, which require high throughput and low latency. Other video and audio outputs are not used in the current implementation of the platform.

The platform also features an infrared proximity sensor connected to the GPIO pins, which allows the platform to detect obstacles in front of it and automatically brake before crashing into them. This feature works in both automatic and manual modes. An obstacle in the sensor's range also prevents the operator from manually accelerating. The effective range of the proximity sensor is approximately 30 to 50 centimeters, which is judged to be sufficient when driving at slow speeds.

A photo of the latest iteration of multi-purpose automated vehicular platform prototype is displayed in Figure 4.1. The figure shows the Raspberry Pi connected to the power feeding circuit via the GPIO pins. Power is supplied from the circuit via the micro-USB cable. The LTE modem is connected upright to one of the Raspberry Pi's USB ports near the front. The battery pack is mounted at the bottom of the platform and the proximity sensor and camera are mounted at the front of the

***Table 4.3*** *Technical specifications and features of the multi-purpose vehicular platform prototype*

| | |
|---|---|
| **Framework** | Disassembled radio-controlled car<br>4 wheels and 2 motors |
| **Computing unit** | Raspberry Pi 3 model B |
| **Operating system** | Raspbian Jessie Lite (Linux-based) |
| **Radio access technologies** | BCM43438 Wi-Fi IEEE 802.11 b/g/n<br>ZTE MF831 LTE USB modem<br>Bluetooth Low Energy |
| **Battery** | 2-cell 7.2V LiIo battery pack |
| **Camera** | Raspberry Pi Camera Module v2, 8 Megapixels |
| **Video stream** | Up to 720p @ 30 fps tested working smoothly |
| **Video compression** | Hardware encoded H.264<br>MJPEG and raw formats also available |
| **Sensors** | Infrared proximity sensor |

platform. The technical details and features of the multi-purpose vehicular platform prototype are summarized in Table 4.3.

A custom application written in Python 3 is responsible for outputting signals via the GPIO pins to control the motors according to the instructions it receives from the remote client controlled by the user. The application also monitors the input from the proximity sensor so it can send the signal to brake if the sensor detects an obstacle in front. The wireless (Wi-Fi) driver and the LTE modem are periodically polled for the current signal level and the information is forwarded using the respective radio access technology (RAT) along with the latency measurement from that RAT. Video feed received from the camera is encoded in hardware with minimal latency and sent to the remote client via one RAT at a time using UDP (User Datagram Protocol). The RAT used can be changed at will in less than a second or the change can be automated based on the latency and signal strength measurements of each RAT.

Likewise, on the user side, a custom remote client application written in Python 3 receives the measurements and the video data from the platform and displays them to the user. The user interface of the application is pictured in Figure 4.2, which displays the video feed, the latency, and video bitrate measurements and the radio access technology currently used to stream the video data. The client-side application receives inputs from the user to instruct the vehicular platform to drive forward or backward, turn left or right, or force changing the RAT used to stream video data. The application sends the commands using UDP to the vehicular platform either via a specified RAT or duplicated over all the available RATs for increased reliability


***Figure 4.2*** *A screenshot of the vehicular platform's user interface featuring the video feed. In the video feed (1) one of the Wi-Fi access points and (2) a room with an LTE base station is shown. Information about the (3) current latency on each RAT, (4) video bitrate measurements and (5) the radio access technology currently used to stream the video data is displayed as well.*

and lower latency. If instructions are duplicated, they are marked with an ID so that the platform does not execute the same command twice.

For the third phase of testing (Section 5.4), MPTCP support was added to both the platform and the remote client. MPTCP was used only for testing throughput improvements in general since the custom application only uses UDP for communication.

## 4.4 Challenges and limitations

This section discusses some of the solved and to-be-solved challenges and limitations that were met with during the implementation process. Workarounds, proposed alternative solutions or other actions taken are briefly presented.

- There are no readily available commercial mmWave (IEEE 802.11ad) solutions or devices suitable for the platform on the market as of this writing. In order to test mmWave performance as one of the radio access technologies within the testing network, suitable equipment has to become available first. In the meanwhile, tests will be performed using Wi-Fi and LTE.

- As the platform is intended for indoor use, GPS cannot be utilized reliably for positioning. Positioning data is a critical component needed to implement the planned automated modes. Indoor positioning solutions should be researched in more detail. Line tracking could be considered as an alternative solution in order to enable simple automated scenarios. Manual mode is sufficient for the research purposes of this thesis.

- Initial design of the platform included one battery pack for the motors and a separate one for the Raspberry Pi. However, the framework could not handle the weight of both batteries and would only stutter forward slowly when loaded with both batteries. As a solution, one of the battery packs was removed and a custom power feeding circuit was designed by the research group members to accommodate the power needs of the motor and Raspberry Pi with a single battery pack.

- The LTE USB modem used officially supports only the Windows and macOS operating systems. Additionally, in its default state, the modem acts as a router and performs an additional NAT on top of the one the LTE side of the test network already does. These issues were circumvented by putting the LTE modem into a serial modem mode and operating the modem with utilities provided by the Raspbian package repository instead of the software provided with the modem.

- Neither the kernel available for the Raspbian operating system of the Raspberry Pi nor the official Linux kernel support MPTCP as of this writing. Therefore a custom kernel had to be compiled for the Raspberry Pi as well as the Linux-based client device in order to enable the use of MPTCP in the third phase of testing.

- As found out from the MPTCP throughput measurement results shown in Section 5.4, the Raspberry Pi lacks the processing power to handle more than 40-50 Mbps of network traffic. Thus, it cannot utilize the full capacity provided by the use of MPTCP. As a workaround, another custom kernel with MPTCP support was compiled for a laptop to be used as an alternative UE for testing the full potential of MPTCP.

The above were the most significant limitations and challenges encountered during the implementation and testing processes. Experience gained from developing solutions to these problems can be put forward in the continuation of the project and other future projects.

# 5. TESTING SCENARIOS AND RESULTS

In this chapter, the testing scenarios and results are presented. Testing was divided into three phases. The first phase of testing consists of utilizing Jolla smartphones in a simple heterogeneous network with LTE and Wi-Fi as the radio access technologies of choice. The second phase incorporates the multi-purpose vehicular platform described in Chapter 4 into the testing scenarios and introduces a refined and expanded test network. During the third phase, MPTCP performance on the local server and on the vehicular platform was evaluated.

The structure of this chapter is as follows. First, the testing methodology is explained in Section 5.1. The testbed network architectures and the testing scenarios are detailed at the beginning of the section for each testing phase. The three testing phases and their results are described in Sections 5.2 through 5.4.

## 5.1 Testing methodology

This section explains the applications and methods used to acquire the results. The main performance metrics considered in the testing scenarios – *latency*, *throughput* and *reliability* – were defined in more detail in Section 2.1. Received signal strength indicator (RSSI) is used in place of signal-to-noise ratio (SNR) to describe the signal quality because it is easier to measure. RSSI is detailed in Section 5.1.2.

The baseline logical topology of the test network located at Tampere University of Technology (TUT) is shown in Figure 5.1. The UE (user equipment) can connect to a device acting as the server located in the TUT network using either Wi-Fi or LTE, or both. The LTE side is routed to an EPC (Evolved Packet Core) located at Aalto University in Espoo via a VPN (virtual private network) connection in the framework of the 5th Evolution Take of Wireless Communication Networks (TAKE-5) project [62]. This VPN connection is estimated to cause an additional delay of approximately 5 milliseconds to the connections routed over LTE based on the round trip time between the TUT server and the EPC.

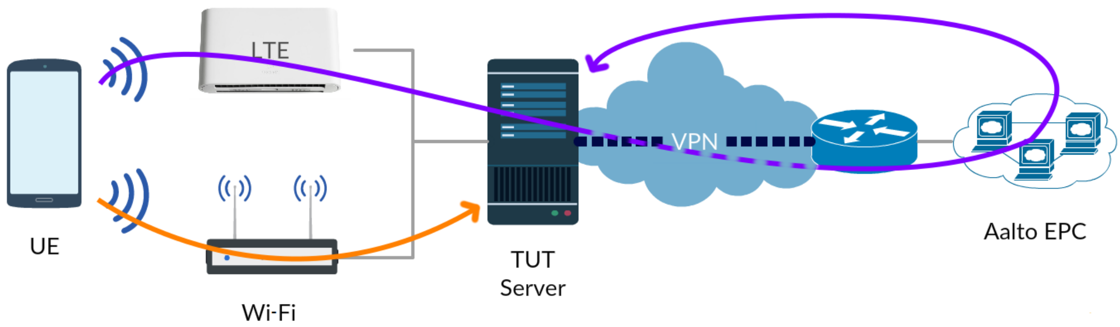



***Figure 5.1*** *Baseline logical topology for the test network detailing the path for the connections over Wi-Fi and LTE.*

### 5.1.1 Testing applications

Throughout the testing phases, various applications were used to obtain results. This section introduces all of the applications utilized. The primary testing applications were custom-made Python scripts because the readily available testing applications are not made with multipathed heterogeneous networks in mind, and as such, they are generally limited to measuring one path at a time. While in some cases it is possible to launch an instance of the application for each available RAT, combining the results in a meaningful way can be tricky.

Applications that use TCP (Transmission Control Protocol) can use MPTCP (Multipath Transmission Control Protocol) if the devices at both ends of the connection support MPTCP and are configured to use it. However, applications that do not use TCP, such as live video streaming or *ping*, cannot utilize this option. Custom multipath aware applications that use UDP were created to solve this problem.

The following applications were used for producing results:

- *Ping duplicator* – A simple custom Python application which on the client side sends a numbered UDP packet via each available RAT at specified intervals for a predetermined amount of time. Information about which RAT was used and when the packet was sent is also included in the packet. On the server side, the server simply echoes the packet back to the source. If the client receives a packet back, it calculates the round trip time (RTT), i.e. how long it took for the packet to travel back and forth. Finally, the client plots a scatter plot detailing the RTT for each packet that was not lost on the way.
- *Vehicular platform control application* – The operation of the application was

described in general in Section 4.3. Here the metrics gathered by the application are detailed. On the platform side, the application keeps track of the RTT and the signal strength for each RAT in one-second intervals and reports the metrics to the remote client. On the remote client side, the application monitors the bitrate of the video it receives and the throughput of each RAT. All connections of the application use UDP.

- *iPerf*[1] – This application is used to measure the maximum available throughput on each RAT. The application supports TCP, UDP, and SCTP (Stream Control Transmission Protocol) by default. When both the client and the server support MPTCP and they are configured to use it, the underlying network stacks of the operating systems automatically convert TCP connections to MPTCP connections, so iPerf can be used to measure throughput in multi-pathed networks in this case.

While not directly used for testing, *Wireshark*[2] is an application that can be used to capture and analyze network traffic. The application was widely deployed on devices part of the test network during the testing process to debug and understand what was happening in the test network.

During the testing process, applications were run on both the UE and another device located in the TUT network with one end acting as a client and the other as a server depending on the application. Testing scenarios were run through at least five times to ensure that the results were coherent.

### 5.1.2 Received Signal Strength Indicator

Cellular devices that comply to the 3GPP TS 27.007 [63] (3rd Generation Partnership Project Technical Specification), report the signal quality as an RSSI (Received Signal Strength Indicator) value when queried with the AT+CSQ (Signal Quality) command. RSSI is reported either as an integer ranging from 0 to 31, or 99 when the signal strength is unknown. According to the specification, the RSSI value corresponds to a signal with a power level of -113 dBm or less when 0, and -51 dBm or greater when 31. For RSSI values from 1 to 30, Formula 5.1 can be used to determine the signal strength in dBm [63]:

$$P_{dBm} = 2 \cdot RSSI - 113, RSSI \in [1, 30], \tag{5.1}$$

[1] https://iperf.fr/

[2] https://www.wireshark.org/

where RSSI is the integer signal quality value as reported by the cellular device. Higher values of $P_{dBm}$ are better. Table 5.1 describes how to interpret the obtained $P_{dBm}$ values.

***Table 5.1*** *Signal strength dBm value descriptions based on [64, 65]*

| Signal strength (dBm) | Description |
|---|---|
| -60 or higher | Excellent |
| -61 to -75 | Good |
| -76 to -80 | Fair |
| -81 to -89 | Poor |
| less than -90 | Bad |

The AT+CSQ command is used during the testing scenarios in order to monitor and obtain the LTE signal strength measurement. For Wi-Fi, the operating systems of the UEs used for testing are capable of reporting the signal strength directly in dBm values.

## 5.2 First phase test scenarios

### 5.2.1 Initial testbed architecture

Before the multi-purpose vehicular platform prototype was developed and built, Jolla smartphones running the Sailfish OS were used to run through testing scenarios in the initial heterogeneous test network. Relevant technical details of the Jolla phones are listed in Table 5.2. The Jolla phones are equipped with LTE and Wi-Fi interfaces which can be used simultaneously after tweaking the settings and turning off the automatic disabling of the LTE interface when Wi-Fi is connected.

***Table 5.2*** *Relevant technical specifications of the Jolla phones*

| | |
|---|---|
| **Operating system** | Sailfish OS 2.0.1.11 (Taalojärvi) |
| **Radio access technologies** | **Wi-Fi** IEEE 802.11 b/g/n<br>GSM / HSPA / **LTE**<br>Bluetooth 4.0 |

The technical specifications of the initial test network are listed in Table 5.3 and the logical topology of the initial test network is shown in Figure 5.2. The Wi-Fi part of the test network comprises a Linksys WRT1900AC wireless access point. The LTE part of the test network is formed by two Ericsson RBS 6402 indoor picocell base

*Table 5.3 Technical specifications of the initial test network and testing scenario*

| | |
|---|---|
| **User equipment** | Jolla smartphone |
| **Server** | Virtual machine located in TUT's network |
| **LTE base stations** | Two Ericsson RBS 6402 indoor picocell base stations |
| **Wi-Fi access point** | One Linksys WRT1900AC access point<br>IEEE 802.11 b/g/n/ac<br>OpenWrt |
| **Testing application** | Ping duplicator (see Section 5.1.1) |
| **Metrics** | Latency and reliability |

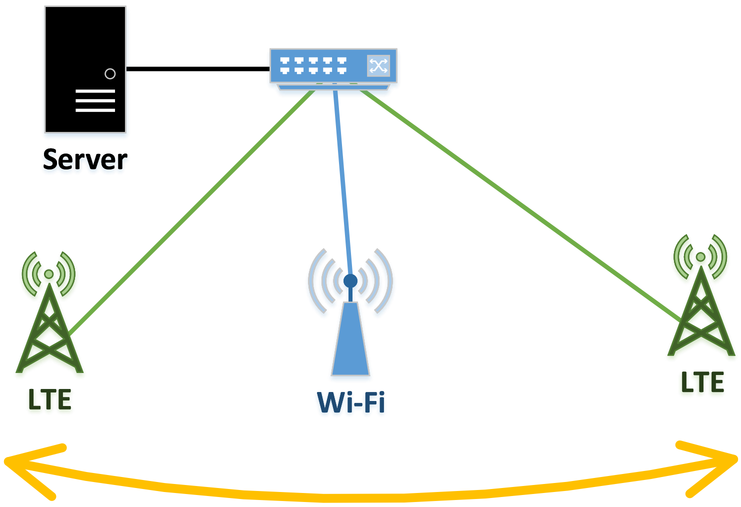



***Figure 5.2*** *Simplified logical topology of the test network. Approximations of the physical locations of the Wi-Fi access point (AP) and LTE base stations (BS) are shown, and the path of the user carrying the UE is marked with a double-headed arrow.*

stations. The access points and base stations are located inside rooms alongside a long corridor in a building located at Tampere University of Technology as described in Figure 5.2. The user carrying the UE is walking along the corridor.

At the beginning of the testing scenario, the UE establishes connectivity to the Wi-Fi access point and one of the LTE base stations. The user carrying the UE is located near one of the LTE base stations. Next, the test application *ping duplicator* is started and the UE begins sending duplicated UDP packets over both the Wi-Fi and LTE connections to the server. The user starts walking slowly along the corridor, towards the location of the Wi-Fi access point and the other LTE base station. The test ends when the user reaches the location of the second base station.

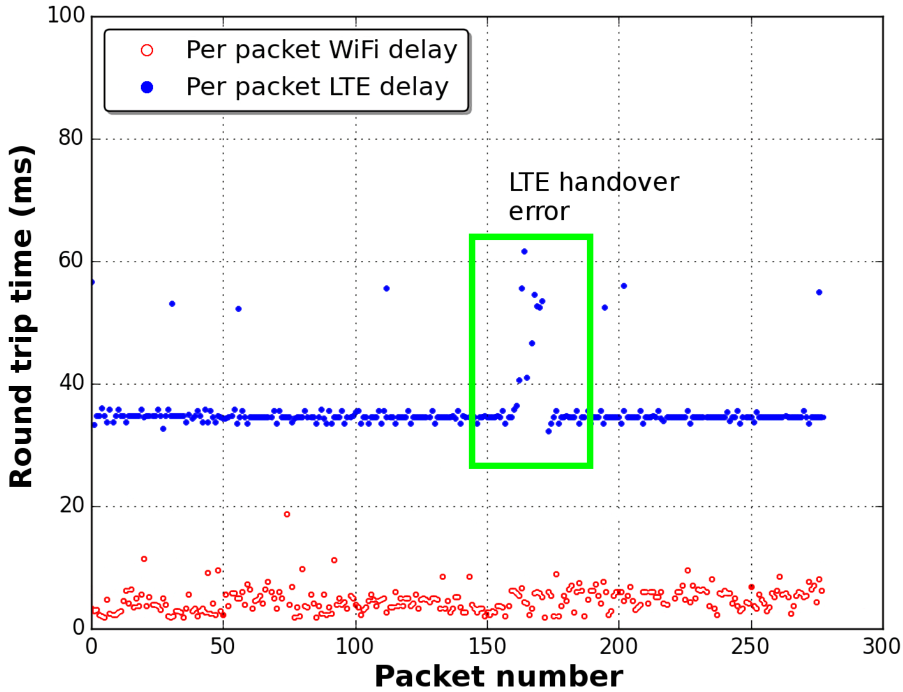
The main objective of this initial testing scenario is to show that in heterogeneous networks it is possible to compensate for interruptions, congestion, coverage holes or other problems in one RAT by sending the data via other RATs instead. It is assumed that there is a coverage hole in the LTE network in between the nodes in this scenario.

### 5.2.2 Results

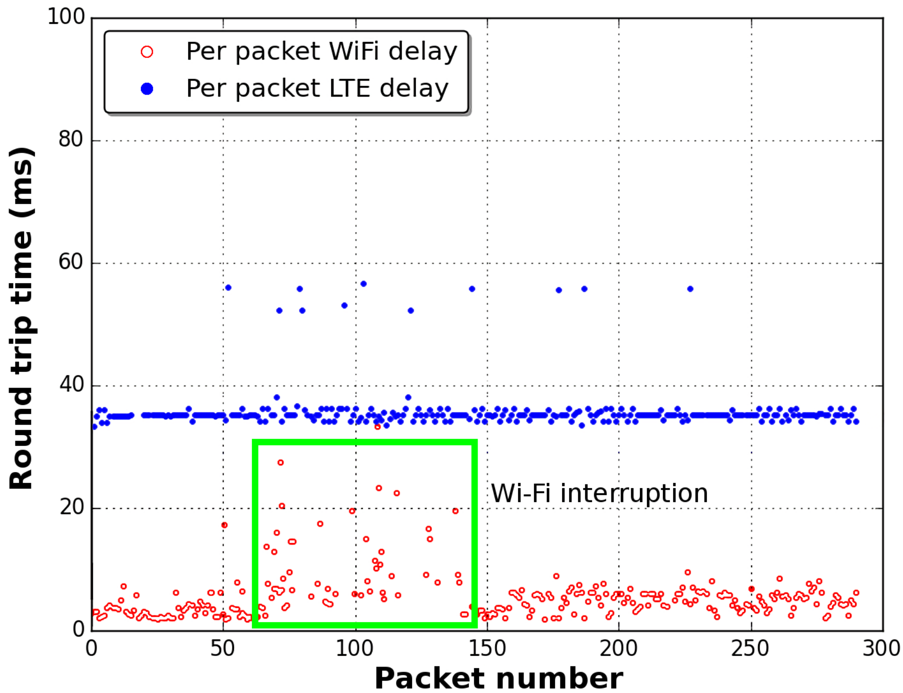
After running through the testing scenario five times, it was concluded that the assumed coverage hole was either smaller than expected or non-existent as no significant consistent connection problems were detected. However, during one of the testing runs, according to Wireshark logs, an error happened during the connection handover from the first LTE base station to the second LTE base station, which caused a brief interruption in the LTE connection. The scatter plot from this testing run is shown in Figure 5.3(a). The hollow dots show the per packet delay of Wi-Fi and the solid dots show the per packet delay of LTE. The total amount of packets was close to 300 per RAT and the interval between packets was set to 200 milliseconds. No overall packet loss was detected in any of the testing runs despite the connection error on LTE. In other words, none of the duplicated packets were lost on both Wi-Fi and LTE. Thus, the objective of the testing scenario was accomplished.

However, the lack of any coverage hole on LTE prompted an experiment to execute the testing scenario in an alternative way: The initial setup is the same, but the user starts walking *away* from the access points and the LTE base stations. When the user notices that packet losses start happening on Wi-Fi due to the distance and resulting poor signal, the user turns back. The test ends when the user has returned to the start location. One of the scatter plots from this alternative testing scenario is shown in Figure 5.3(b). The parameters for the test were the same as above. Results were similar: No overall packet loss was detected in any of the testing runs despite the packet losses on Wi-Fi.

In conclusion, the packet duplicating method over multiple RATs improves reliability by reducing packet loss when using unreliable transport protocols such as UDP in use cases where low latency is a priority, and therefore it is not desirable to use TCP. Packet duplicating did not improve the latency in any meaningful way in this scenario because the measured latencies were consistently lower on Wi-Fi partly due to the unbalanced structure of the test network and because the loads on the networks were practically non-existent. However, it is not efficient to be constantly sending duplicate packets due to lower energy efficiency and congesting the network with redundant traffic. These results were used to refine the testing scenarios in the second phase of testing.




(a) Example of LTE interruption during the test




(b) Example of Wi-Fi interruption during the test

***Figure 5.3*** *Examples of connection interruptions during the test. The LTE interruption was caused by an error during the handover process. The Wi-Fi interruption was caused by walking away from the access point until the signal quality went down enough to cause problems with the connection.*

## 5.3 Second phase test scenarios

### 5.3.1 Refined testbed architecture

For the second phase of testing, the multi-purpose vehicular platform prototype detailed in Chapter 4 was built. Additionally, the Wi-Fi portion of the testing network was expanded from one access point to three access points. The Wi-Fi part of the test network was now composed of three Cisco Air-LAP1142N wireless access points. The LTE part of the test network still consisted of the two Ericsson RBS 6402 indoor picocell base stations. The access points and base stations were relocated to an L-shaped corridor as shown in Figure 5.4, as it was not possible to create large enough coverage holes in the previous test network setup. In the refined testing scenario, the Wi-Fi AP2 is turned off in order to create a coverage hole in the Wi-Fi part of the test network. Other improvements over the initial testing scenario include the ability to measure the signal strengths of the Wi-Fi and LTE connections and larger control over the data flows from the vehicular platform to the remote client and back. The technical specifications of the refined test network and testing scenario are listed in Table 5.4

***Table 5.4*** *Technical specifications of the refined test network and testing scenario*

| | |
|---|---|
| **User equipment** | Multi-purpose vehicular platform |
| **Server** | Laptop used as a remote client for the platform |
| **LTE base stations** | Two Ericsson RBS 6402 indoor pico base stations |
| **Wi-Fi access points** | Three Cisco Air-LAP1142N access points<br>IEEE 802.11 b/g/n |
| **Testing application** | Vehicular platform control application (see Section 5.1.1) |
| **Metrics** | Latency, reliability, signal strength |

At the beginning of the refined testing scenario, after the vehicular platform has established connectivity to one of the Wi-Fi access points and to one of the LTE base stations, the remote client establishes at least four connections to the vehicular platform:

- a control connection, which is used to transmit instructions such as *turn left* or *change video stream to LTE* to the vehicular platform;
- a connection for the video stream, which is used solely to transmit the video data from the vehicular platform to the client;
- two telemetry connections, one for each RAT, which are used to measure the latency and transmit other telemetry information such as signal strength.

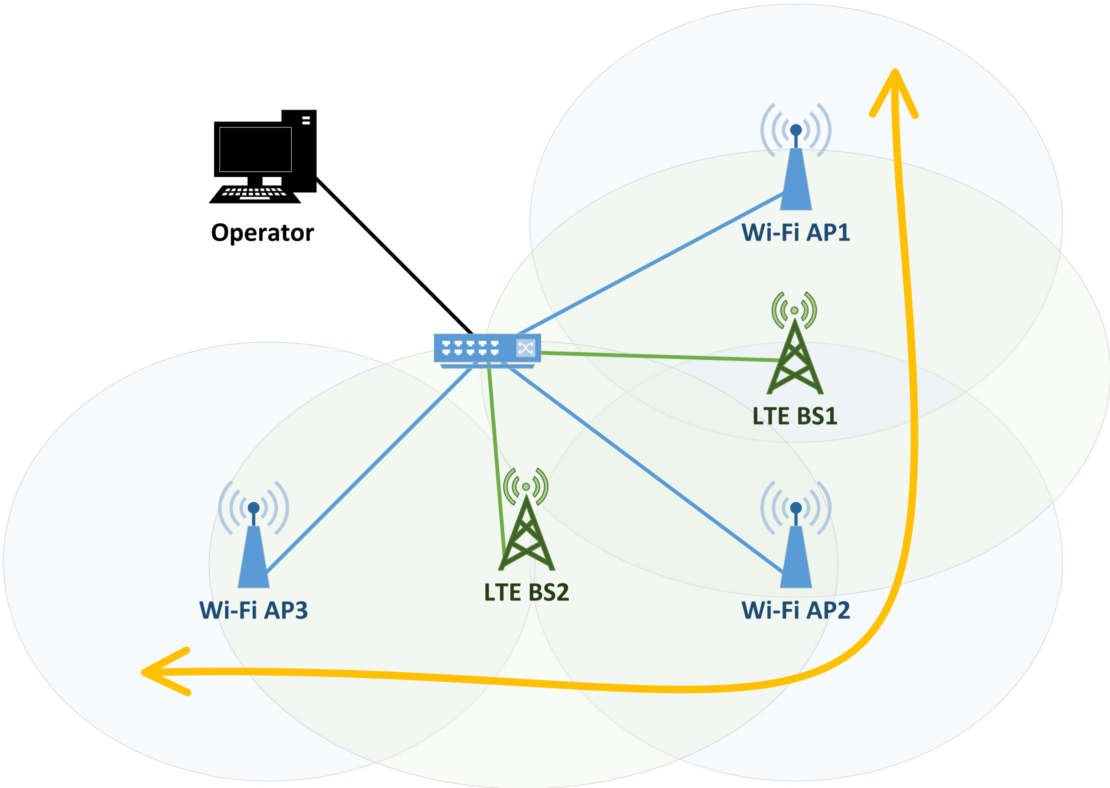



***Figure 5.4*** *Simplified logical topology of the refined test network. Approximations of the physical locations of the access points (AP) and base stations (BS) are shown, and the path of the vehicular platform is marked with a double-headed arrow.*

The RATs used for the control connection and video stream can be chosen and changed freely. Alternatively, the control connection can be duplicated over all available RATs for improved reliability and lower latency. In this scenario, video is streamed over Wi-Fi at the beginning and control connection is duplicated over both RATs.

The starting location for the vehicular platform is at the end of the corridor, past Wi-Fi AP1. The operator controlling the vehicular platform from the remote client starts driving slowly along the corridor towards Wi-Fi AP2, which has been turned off. When the vehicular platform approaches the corner in the corridor, the operator changes the video stream to LTE from Wi-Fi. This could be set to be done automatically based on the telemetry data, but in this scenario, the changes are done manually for the sake of consistency. When the vehicular platform approaches Wi-Fi AP3, the operator changes the video stream back to Wi-Fi. After driving past Wi-Fi AP3, the operator turns the vehicle around and starts driving back along the same route while changing the video stream to LTE and back at the appropriate locations. The test ends when the vehicular platform returns to the starting location. The objectives of this refined testing scenario are:

- to show that in heterogeneous networks it is possible to compensate for interruptions, congestion, coverage holes or other problems in one RAT by sending the data via other RATs instead;
- to show that by duplicating data over multiple RATs, it is possible to achieve lower overall latency when compared to a single RAT. This objective could not be realized in the initial testing scenario.

### 5.3.2 Results

Figure 5.5 shows the times when the video stream was connected over Wi-Fi and when it was connected over LTE during one of the test runs. Additionally, the throughput generated by transmitting the video is shown. The almost non-existent gaps in throughput when switching from a RAT to another indicate that the transition happens rather smoothly. However, the transition is not entirely transparent to the operator, as the operator can notice the video flicker for an instant when the switching happens. From a QoE (Quality of Experience) point of view, the visual experience is not yet as good as it could be, but controlling the vehicular platform feels smooth, owing to the duplicated control packets.

Figure 5.6 shows the signal strength levels for Wi-Fi and LTE as a function of time from the same test run as in the previous figure. It can be noticed that while the polling rate for Wi-Fi and LTE signal strengths are the same (one second), the LTE USB modem seems to update its RSSI value erratically (i.e., at random intervals) when compared to the built-in Wi-Fi chip of the Raspberry Pi. From the figure, it can be roughly seen when the vehicular platform approaches the Wi-Fi AP1, continues past it to LTE BS1, turns around the corner to LTE BS2, reaches the range of Wi-Fi AP3 and drives past it to turn around and backtrack through the same route in reverse. Figures 5.5 and 5.6 should be compared together to see how the RAT changes tie in with the fluctuations in signal strength. In general, the connection with a relatively stronger signal is used.

Figure 5.7 shows the latency metrics collected from a different testing run as the previous two figures, and as such, this figure is not directly comparable with them. As the general flow of the testing scenario is the same, similar patterns can be noticed. A 10-second moving average for the RTT was used to smoothen out the graph, which is the reason why the x-axis starts from 10 instead of 0. The main point of this figure is to show that when duplicating data over multiple RATs, it is possible to achieve noticeably lower overall latency than when compared to a single RAT. Thus, the second objective of this testing scenario was fulfilled.

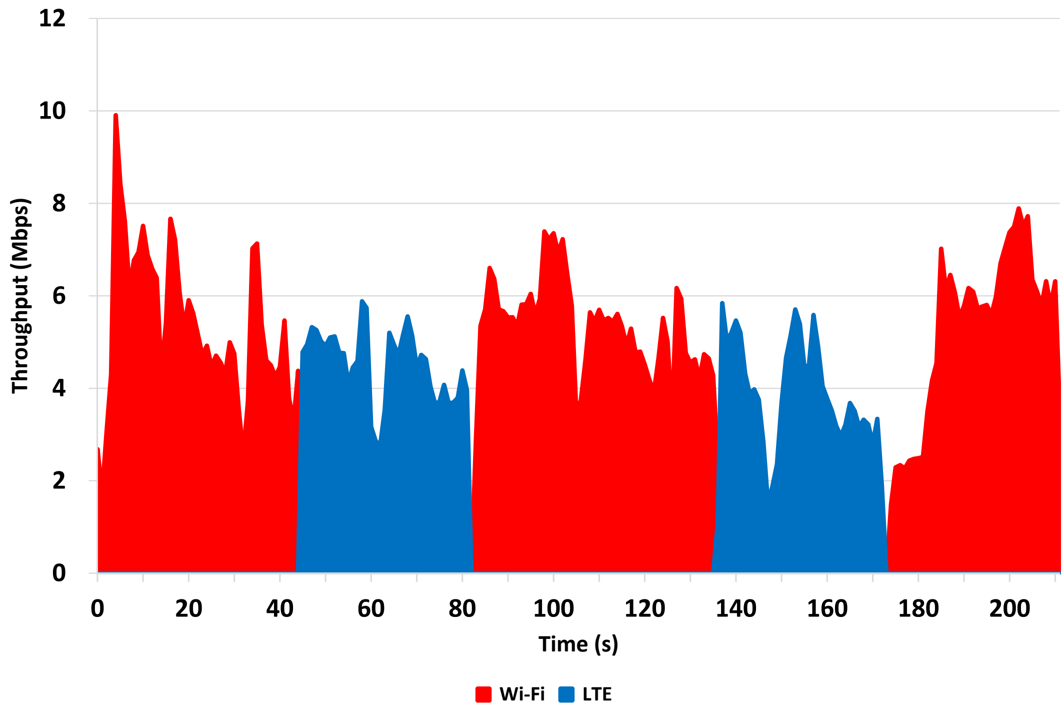



***Figure 5.5*** *Video stream connectivity breakdown shows the times when the video stream was connected over Wi-Fi and when it was connected over LTE. Additionally, the throughput generated by transmitting the video is shown.*

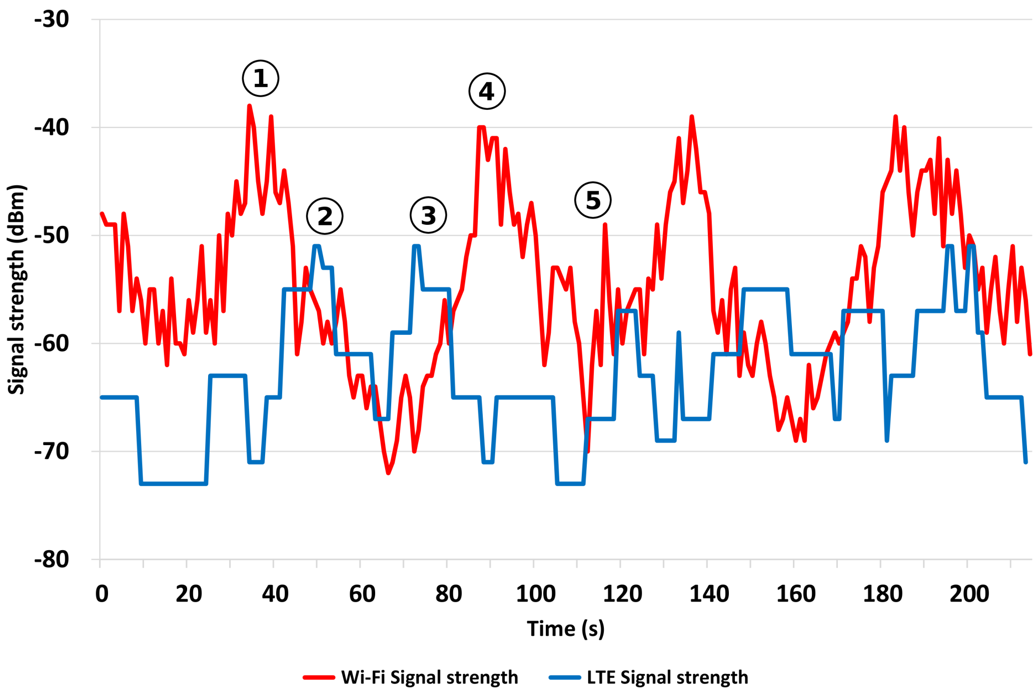



***Figure 5.6*** *Signal strengths in dBm for Wi-Fi and LTE as a function of time from the same test run as Figure 5.5. The graph shows roughly when the platform reached each access point and base station along the path: (1) Wi-Fi AP1, (2) LTE BS1, (3) LTE BS2, (4) Wi-Fi AP3 and (5) the turning point past Wi-Fi AP3. After point (5) the platform turned around and traversed the same path in reverse.*

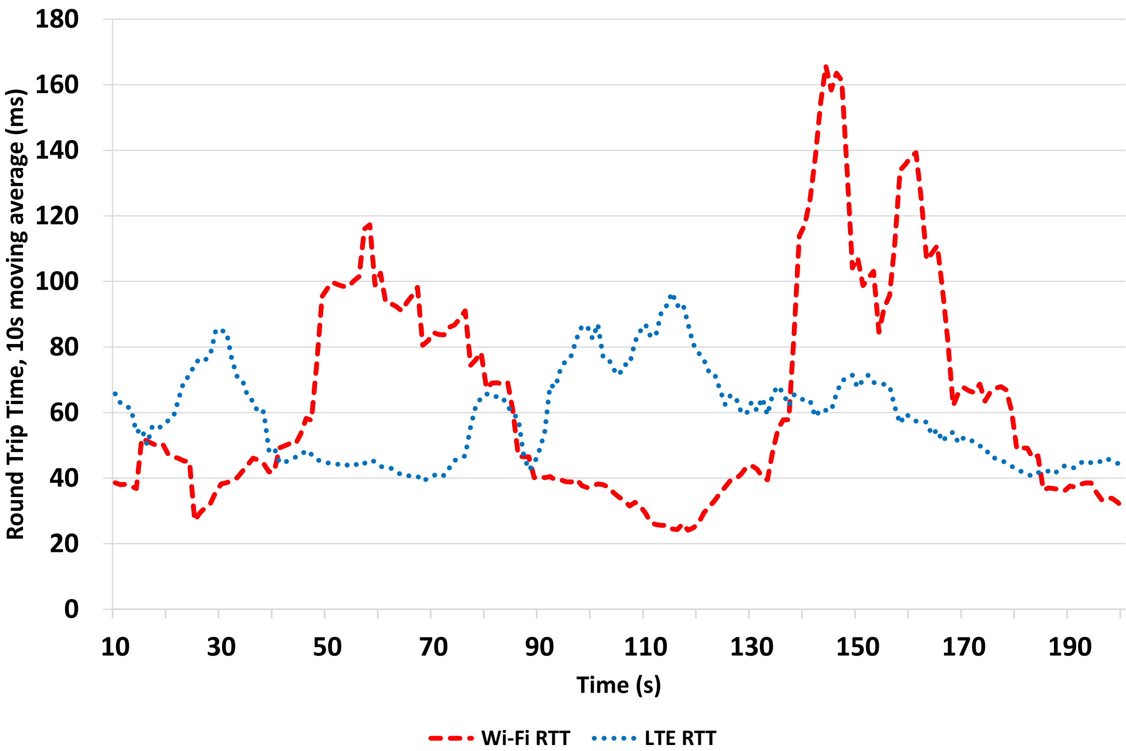



***Figure 5.7*** *Round trip time measurements for the second phase testing scenario. A 10-second moving average was used to smoothen out the graph, which is the reason why the x-axis starts from 10 instead of 0.*

In conclusion, it was shown that by directing the heavier data flows, such as video streams, at opportune moments to another RAT, it is possible to achieve better performance in terms of latency and a more stable or better quality connection in terms of signal strength. A future research challenge is to utilize the results obtained from this testing scenario and develop a solid algorithm to automatically change the heavier data flows optimally. While sending redundant copies of large amounts of data to the Internet is undesired from the network's point of view as it causes congestion, low amounts of important traffic, such as control signals, could be duplicated constantly to consistently improve reliability and latency. In a separate network environment, such as the intranet of a factory, even large amounts of mission-critical data could be duplicated freely, as it would not cause congestion to the Internet.

## 5.4 Third phase test scenarios

For the third and final phase of testing, the vehicular platform and the local server were upgraded to support MPTCP and configured to use MPTCP instead of TCP whenever possible. The test network is otherwise identical to the one used in the second phase, except that the Wi-Fi AP2 has been re-enabled. The technical specifications of the final test network and testing scenario are listed in Table 5.5.

***Table 5.5*** *Technical specifications of the final test network and testing scenario*

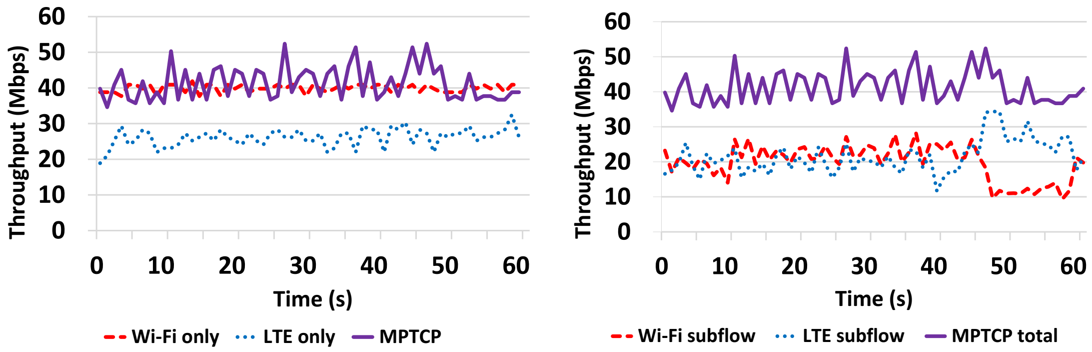
| | |
|---|---|
| **User equipment** | Multi-purpose vehicular platform<br>Laptop |
| **Server** | Virtual machine located in TUT's network |
| **LTE base stations** | Two Ericsson RBS 6402 indoor pico base stations |
| **Wi-Fi access points** | Three Cisco Air-LAP1142N access points<br>IEEE 802.11 b/g/n |
| **Testing application** | iPerf with MPTCP (see Section 5.1.1) |
| **Metrics** | Maximum throughput |

The objective of the final testing scenario is to demonstrate the potential performance gains from utilizing multipath protocols in terms of throughput. The application used to measure throughput is *iPerf* with MPTCP as the transport protocol. The starting location for the vehicular platform in this scenario does not matter as long as it has connectivity over both Wi-Fi and LTE. The operator controlling the vehicular platform from the remote client starts iPerf in TCP server mode on a VM (Virtual Machine) server located inside the university's network and starts iPerf in TCP client mode on the vehicular platform. The throughput test is run for a period of one minute. The network stacks of the operating systems of the UE and the server automatically convert TCP connections to MPTCP connections as they are configured to do so. The operator emulates a mobile user by driving around the corridor for the length of the test without any video being transmitted. Finally, to get a point of reference, the same testing scenario was repeated with only the Wi-Fi connection active and only the LTE connection active.

### 5.4.1 Results

After the first few trial runs of the testing scenario, it was noticed that the Raspberry Pi was unable to fully harness the improved throughput provided by the use of MPTCP as seen from the sample results shown in Figure5.8(a), which display the throughputs for the Wi-Fi only trial, LTE only trial and MPTCP trial. The throughputs for the Wi-Fi subflow and the LTE subflow in the MPTCP trial can be seen in Figure5.8(b)

The throughput appears to cap at around 40 Mbps for both the MPTCP trial and Wi-Fi only trial. It was assumed that the throughput is limited by the hardware of the Raspberry Pi. In order to verify this theory, a more powerful UE was needed.




(a) Separate throughput measurements (b) MPTCP subflow throughputs and total throughput

***Figure 5.8*** *Samples of throughput measurements on the mobile platform by using MPTCP. Throughputs are limited by the processing power of the mobile platform.*

Thus, a laptop was upgraded to include MPTCP support. Relevant technical specifications of the laptop are listed in Table 5.6. The same LTE USB modem was used for the laptop to keep the testing environment as similar as possible.

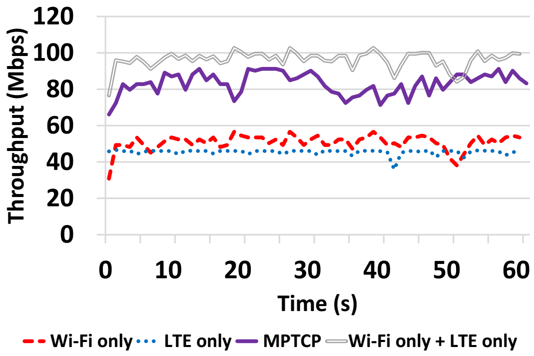
***Table 5.6*** *Relevant technical specifications of the laptop used as a UE*

| | |
|---|---|
| **CPU** | Intel Core i5-5200U @ 2.20GHz |
| **Operating system** | Fedora 26 (Linux-based) |
| **Radio access technologies** | Intel Wireless 7265, IEEE 802.11 b/g/n/ac<br>ZTE MF831 LTE USB modem |

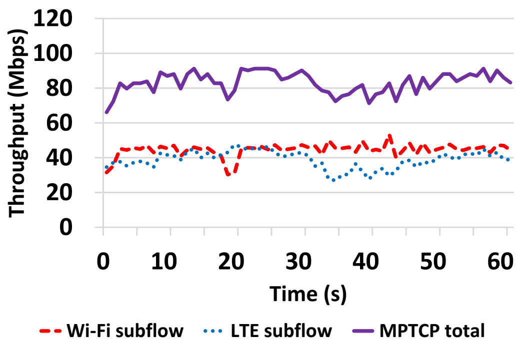
The results from one of the iPerf connection tests by using the laptop as a client in Wi-Fi only trial, LTE only trial and MPTCP trial are shown in Figure 5.9(a). The throughputs for the Wi-Fi subflow and the LTE subflow in the MPTCP trial can be seen in Figure 5.9(b). The results confirm the hypothesis of the vehicular platform lacking the resources to process the full amount of traffic that would be possible by using MPTCP with all of the available RATs. Nevertheless, the objective of the final testing scenario was accomplished.

The results also show that the throughput of MPTCP does not quite reach the theoretical maximum calculated by summing up the results of the Wi-Fi only and LTE only trials. Methods to improve this ratio while keeping the operation of the protocol fair might be an interesting research topic for the future.

In conclusion, it was established that the hardware of the Raspberry Pi is not able to handle the full amount of throughput that would be available by the use of MPTCP. A laptop was used as the UE for the throughput performance test instead and it was




(a) Separate throughput measurements




(b) MPTCP subflow throughputs and total throughput

***Figure 5.9*** *Samples of throughput measurements on a laptop by using MPTCP. The "Wi-Fi only + LTE only"series displayed with a gray line is a theoretical maximum MPTCP could have possibly reached in this particular case if it had performed as well as the sum of its parts.*

shown that by utilizing a multipath protocol to transfer data over multiple RATs, it is possible to achieve significantly better throughput at the cost of increased energy consumption. The exact possible drawbacks or benefits of utilizing multiple RATs at the same time from the energy efficiency point of view remain to be determined in future research.

# 6. CONCLUSIONS

This chapter concludes the thesis by summarizing the topics discussed in this work. As the numbers of users and amounts of traffic in the Internet keep rising exponentially and the requirements of novel applications are becoming more stringent, there is a clear need for new networking solutions. One of the key concepts in solving the challenges of the upcoming years will be heterogeneous networks, where the users can gain benefits by either being connected to multiple different networks simultaneously or smoothly changing from one network to another based on their needs.

However, there is a problem that has to be solved before the concept of heterogeneous networks can be fully realized: the current protocols of today's Internet cannot be aware of more than a single address and a single connection path at a time, and introducing new multipath aware protocols to the entirety of Internet in a way that would work harmoniously with all existing parts is time-consuming and challenging, to say the least. Nevertheless, there are efforts underway to include MPTCP (Multipath Transmission Control Protocol) support to the official Linux kernel, which would accelerate the adoption of multipath protocols significantly. Out of the big industry players, Apple has implemented MPTCP support in their devices.

When we reach widespread access to multipath aware protocols, the main question will be: how can we utilize the concept of heterogeneous networks and the simultaneous connections to multiple networks to improve throughput, latency, and reliability, in addition to making the overall user experience better? In order to find answers to this question, a multi-purpose automated vehicular platform prototype equipped with multiple radio access technologies was built and the process was documented in Chapter 4. Testing scenarios and results were presented in Chapter 5.

Improved throughput potential was demonstrated in Section 5.4 by using MPTCP to transmit data over LTE (Long Term Evolution) and Wi-Fi simultaneously and measuring the maximum throughput. Even though the throughput of MPTCP did not quite reach the theoretical maximum calculated by summing up the results of the Wi-Fi only and LTE only trials, the ability to utilize the nearly full capacity of each available radio access technology on demand is going to be significant in the future mobile networks in terms of user experience. The exact possible drawbacks or benefits of utilizing multiple RATs (radio access technologies) at the same time from the energy efficiency point of view remain to be determined in future research.

A concept for improving latency involves sending copies of same data over all available networks, employing the one that arrives the fastest to the destination and discarding the rest. Sending multiple copies of the same data also creates redundancy, which in turn improves reliability, as it is much more unlikely for all copies of the same data to become lost than for one copy. This concept was shown in practice in Section 5.3. Sending redundant copies of large amounts of data to the Internet is undesired from the network's point of view as it causes congestion. However, in a separate network environment, such as the intranet of a factory, even large amounts of mission-critical data could be duplicated freely, as it would not cause congestion on the Internet. Additionally, having multiple network interfaces active at the same time increases energy consumption. Therefore, a balance should be catered between improving performance, energy efficiency and overloading the networks. This is a topic for future research.

Work on the multi-purpose automated vehicular platform is planned to be continued in the future. There are plans to upgrade the framework of the platform to be able to carry more weight in order to mount an access point on the platform for it to become a moving access point. Indoor positioning is an important feature to be added in order to enable the designed automated operating modes. As novel technology slowly becomes more available, mmWave (millimeter wave) radio is a top candidate to be added into the selection of radio access technologies for the platform.

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